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# Innovative adsorption chiller for marine applications: design and building

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**Abstract**

In this work, the design and building of an advanced adsorption chiller, developed for marine applications, is reported. The realization of this cooling system was financed by the T.E.S.E.O. (*Efficient Technologies for Energy Sustainability and Environmental On Board*) – P.O.N. (Research and Competition 2007/2013) project. The prototype, developed with the aim of increase the cooling power density (*$W/m^3$*), has two main innovative features: a novel three-adsorbers, connected with a condenser and an evaporator, and a hybrid adsorber, with a coating of *FAM AQSOA-Z02* and *Silica Gel* granis. The prototype was designed to produce a Cooling Power about 4 - 6 kW, as function of the operating conditions. A complex system of pipes and valves was realized to manage the external hydraulic circuits, allowing to automatically perform the adsorption cycles, controlled by a control system, realized by the LabVIEW software by National Instruments.


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Keywords: Adsorption heat pumps, Zeolite, Silica gel, Advanced heat exchangers

## 1. Introduction

In recent years, considerable efforts have been made in the area of research and development of thermally driven adsorption cooling systems in order to make them more competitive with traditional vapor compression and liquid absorption ones. Adsorption machines use environmentally friendly refrigerants (e.g. water, ethanol, etc) and can be driven by low grade thermal energy sources like solar energy, industrial/automobile waste heat, cogeneration, etc [1, 2]. Nowadays, the research activity is

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mainly focused to increase the cooling power density to reduce the volume and weight of these machines. In fact, on the one hand bulkiness of these systems can be considered only partially a limiting factors for stationary applications while, on the other hand, it's of great importance in the transport field, where the containment of weights and volumes are an important prerequisite [3, 4]. In this work, the design and building of an advanced adsorption chiller, specifically developed for marine applications, is reported. The prototype, developed with the aim of increasing the cooling power density (*W/m³*), has two main innovative features:

- a novel configuration with three adsorbers connected with a single condenser and a single evaporator. This special layout allows to perform an advanced adsorption cycle, extending the adsorption phase with respect to the desorption one. This management strategy could lead to increasing of power density as reported in [5, 6];
- a hybrid adsorber, based on aluminum finned heat exchangers, containing two different adsorbent material configurations: a coating of Zeolite and loose grains of Silica Gel.

The prototype was designed to produce a Cooling Power about 4 - 6 kW, as function of the operating conditions. The expected cooling power density (*12 kW/m³*) is competitive with commercial machines, like SorTech (*10 kW/m³*) and InvenSor (*7 kW/m³*).

## 2. The prototype

Commonly, adsorption cooling systems are proposed in the two well-known configurations: with a single adsorber and with two adsorbers. In the first configuration, it doesn't produce a continuous cooling power. This problem can be solved using two adsorbers, operating in antiphase with an equal duration of the isobaric adsorption and desorption phases. Studies carried out by Aristov et al [5] and Sapienza et al [6], showed that it is possible to significantly increase the power density, reducing desorption time and increasing adsorption one. To operate this advanced thermodynamic cycle is required a multi-adsorbers system. In this work, we present a novel three adsorbers chiller, designed to work with R=2, where R is the ratio between adsorption time (tads) and desorption time (tdes). The following figure shows a photo of prototype and its layout.

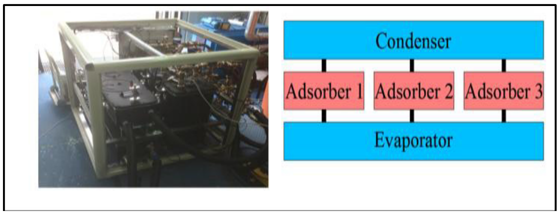


Figure 1. View of the prototype (a) and its schematic layout (b)

The prototype is formed by five vacuum chambers, connected thanks to use of vacuum valves. The following table summarizes the main features of the prototype. In the following subparagraphs the main components of the chiller are described.

Table 1. Main features of the prototype

| | | | |
|---|---|---|---|
| Sizes (L x B x H): | *860 mm x 790 mm x 690 mm* | Adsorbent material | *Zeolite + Silica Gel* |
| Volume: | *0,47 m³* | Expected cooling power: | *4-6 kW* |
| Weight: | *270 kg* | Expected Specific cooling power (volumetric): | *Up to 12,7 kW/m³* |

| | |
|---|---|
| Adsorbers: HExs | *Aluminum finned flat-tube* |

## *2.1. The adsorbers*

The design of the adsorbers (full scale) of the adsorption chiller was made on the basis of the results of a specific experimental activity carried out. Different configurations of adsorbers (small scale) were developed and their potential, in terms of power density, was evaluated experimentally, using a test bench for adsorbers, based on a single bed adsorption chiller, located in the laboratories of the C.N.R. – I.T.A.E. and described in Sapienza et al [6]. This activity allowed to select the optimal configuration, maximizing performance and reducing the capital cost. Several configurations of adsorbers were tested, changing both geometry of adsorbers and adsorbent materials. All adsorbers were made by aluminum finned flat-tube heat exchangers, having an high density of heat exchange area. Two adsorbent materials were used: *FAM AQSOA-Z02* (produced by *Mitsubishi Plastic Inc*) and a commercial microporous *Silica Gel* (produced by *OKER CHEMIE*). The optimal configuration, chosen to realize the adsorbers of prototype, was formed by a coating of zeolite and granules of Silica Gel ($600\ \mu m < d < 700\ \mu m$). This solution represents a good technical / economical compromise to realize an adsorber; in fact:

- coating of innovative zeolite (*FAM AQSOA-Z02*) was realized to improve the thermal efficiency of adsorbers. This material was specifically developed for adsorption machines driven by low temperature heat source. Indeed, it can be desorbed at temperature between 80°C and 90°C. The coating configuration allows to use this expensive material efficiently, due to the optimal thermal contact with the metal surface of the HEx;
- granules of Silica Gel were used to increase the total cooling power.

On the basis of these experimental tests, the heat exchangers of the three adsorbers X (adsorber 1, 2 and 3) were designed. In particular, to optimize the overall dimensions, each adsorber was divided in three smaller adsorbers Y (1.1, 1.2, 1.3, etc). The three adsorbers, assembled in each vacuum chamber, are connected thanks to two hydraulic collectors, welded on the main flange of each adsorber. The main features of the heat exchanger of a single adsorber Y are reported in the following table.

Table 2. Main features of heat exchangers

| | | | | | |
|---|---|---|---|---|---|
| Material: | *Aluminum* | Depth: | *22 mm* | Heat exchange surface: | *800 $cm^2$* |
| Length: | *508 mm* | Height: | *160 mm* | Heat exchange surface for single adsorber: | *24000 $cm^2$* |

Once made the heat exchangers, hybrid adsorbers were realized. To prepare these ones were used two adsorbent materials: a coating of zeolite, deposited on the surface of the finned pack, and granules of Silica Gel, inserted between the fins of heat exchangers. First of all, a coating of Zeolite was applied on the surface of each finned pack. The zeolite used is a *FAM AQSOA-Z02*; it is probably one of the best commercial adsorbents of water vapour for adsorption air conditioning applications, driven by low thermal source. The main properties of this adsorbent material were explained in the work of Freni et al [7]. The coatings, or composite layers, were realized thanks to "*dip coating technique*". The amount of zeolite was chosen to maximize mechanical and adsorbent properties of the coating. Granules of Silica Gel were added to increase the power density. These amorphous materials are formed by aggregation of primary silica particles which size and packing determines the specific surface area, pore size and volume [8]. It is a desiccant with excellent adsorption capacity and it is extremely economical. First of all, thanks to a mechanical sifter, the desired particle sizes were chosen, according to experimental lab test ($600\ \mu m < d < 710\ \mu m$). Subsequently, the granules of Silica-Gel were included inside of the finned packs, where the coatings of zeolite were already present. To prevent the leakage of granules, a wire netting was pasted on the two faces of aluminum heat exchangers thanks to an high temperature adhesive that is insoluble at water vapor, produced inside the chiller. At the end of this phase, nine hybrid heat exchangers were realized. The following table summarizes the main features of the hybrid adsorbers.

Table 3. Main features of adsorbers

| | | | | | |
|---|---|---|---|---|---|
| Total mass metal of adsorbers: | *12,4 kg* | Total mass of silica gel: | *3,1 kg* | Mass metal / Mass ads: | *1,85* |
| Total mass of coating: | *3,6 kg* | Total Mass adsorbent materials: | *6,7 kg* | | |

### *2.2. Evaporator-condenser*

The evaporator and the condenser are based both on two heat exchangers; the first is totally immersed in the liquid phase of refrigerant while the second in contact with the vapor phase. The two heat exchangers are assembled thanks to use of two hydraulic collectors. Thanks to this configuration, it is possible to test if the heat exchanger, positioned in vapour phase, improves vapour flow, increasing the performance of the chiller. The connection between evaporator and condenser is made thanks to lamination valves.

## 3. Prototype management

For the operation and control of the three-bed adsorption system, a complex hydraulic system was realized. The system allows to simulate the three energy sources sinks necessary to reproduce real operating conditions:

- Low temperature line: connected to evaporator;
- Middle temperature line: connected to condenser and to adsorbers, for the adsorption phase;
- High temperature line: connected to adsorbers, for the desorption phase.

The following figure shows the P & I (Piping and Instrumentation) to manage the three adsorbers. To manage these ones, solenoid and check valves were installed. Their control is managed from relay modules.

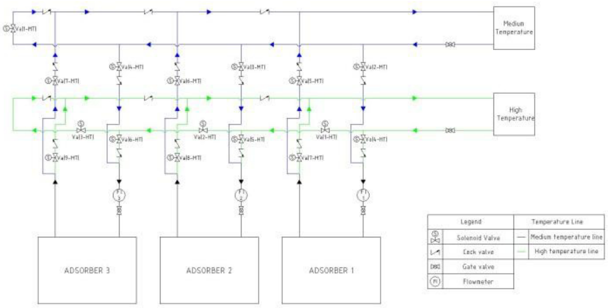


Figure 2. P & I of the management system of the prototype

This hydraulic system is controlled by a control panel, realized by the LabVIEW software by National Instruments.

### *3.1. Working with three adsorbers*

In adsorption chiller, cooling power is produced during the adsorption phase, when the adsorber adsorbs refrigerant fluid from evaporator. Adsorption phase is one of the four phases of a thermodynamic cycle of a classical adsorption machine and, consequently, during the other phases, cooling power is not produced. In general, to resolve this problem, two adsorbers could be the best solution. In fact, in this configuration, evaporator is always connected with one of the two adsorbers. Consequently, continuously cooling power could be produced, without to use of storages. The equation for SCP in an adsorption heat transformation was calculated as ratio between the useful cooling effect, the adsorbent mass (M) and the total cycle time. The experimental tests show that cycle time influences strongly the performance of the adsorption cooling systems. In particular, increasing cycle time, SCP decreases. Moreover, kinetic studies show that desorption time is less than adsorption time. This condition is due to the higher temperature and vapor pressure during the desorption than adsorption. The kinetic results show that, for an optimal ratio tdes / tads, SCP increases compared to classical cycle, where tdes = tads [6]. An increasing of SCP is fundamental because it allows to improve the lightness and the compactness, fundamental parameters for mobile applications. Consequently, to improve the performances of adsorption machines, a reallocation of adsorption/desorption time is necessary. Lab tests, on the particular adsorbers, show that SCP produces the best value for R=2.5 (tads=300 sec and tdes=120 sec). Thanks to these tests, we designed a prototype to work with R=2. This working condition demands to use three adsorbers. The following figure shows the working system of prototype with three adsorbers.

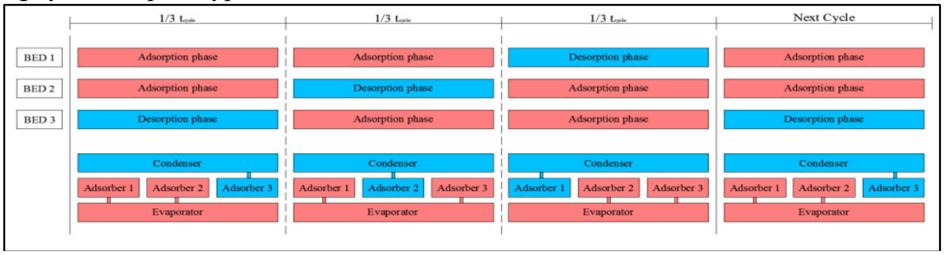


Fig. 3. Operation of adsorption cooling system with two adsorbers

It is possible to note that, in each phase, evaporator is always connected with two of the three adsorbers. From the previous figure, it is possible to note that, for each beds, the adsorption phase is 2/3 of tcycle while desorption phase is 1/3 of tcycle.

## 4. Measurement and control system

The prototype has been provided with a series of transducers in order to monitor and acquire the temporal evolution of the physical parameters of interest (e.g. the temperature, the pressure and the flow). The several transducers used, together with the respective measurement characteristics, are reported in the following table.

Table 4. Main features of sensors.

| Sensor | Measured | Measurement point | Sensor/ Control type | Accuracy |
|---|---|---|---|---|
| $T_1 – T_2 – T_3$ | Temperature | Adsorbers 1, 2, 3 | TC type T, class 1 | ±0.5°C |
| $T_C – T_E$ | Temperature | Evaporator, Condenser | TC type T, class 1 | ±0.5°C |
| $P_1 – P_2 – P_3$ | Pressure | Adsorbers 1, 2, 3 | Piezoresistive Transmitters | ≤ 0,25 % of span |

| | | | | |
|---|---|---|---|---|
| $P_C - P_E$ | Pressure | Evaporator, Condenser | Piezoresistive Transmitters | ≤ 0.25% of span |
| $F_1 - F_2 - F_3$ | Flow | Adsorbers 1, 2, 3 | Ultrasonic flowmeter | ±3% of reading |
| $S_L$ | Level | Condenser | Optoelectronic Liquid Level | ±0.5 mm |

A innovation of this prototype is the control of lamination valves. In fact, on the condenser, thanks to a vacuum flange, a level optoelectronic sensor was installed. This sensor, independent of the features by the fluid, is connected to the relay module of lamination valve. When the refrigerant fluid, inside the condenser, touches the sensor tip, the relay module closes, opening the lamination valves. In this configuration, the transition of refrigerant fluid from condenser to evaporator is fully automated. The flowmeters were inserted to set and control water flow in each adsorber.

All sensors data, together with the vacuum valves and hydraulic ones, are interfaced by a data acquisition system, purchased by National Instruments. They are monitored and controlled by a control system, realized thanks to "LabVIEW 2014" software. Such software allows to monitor and obtain all the physical quantities useful for the operation of the machine and to control solenoid and vacuum valves. Consequently, thank to this software, the operating modes are managed. A control system of the cooling production will be developed in future while, initially, the prototype will be tested on a test bench reproducing fixed operating conditions.

## 5. Conclusion

A prototype of adsorption chiller for marine air conditioning was designed and assembled. The aim has been to realize an adsorption chiller able to perform an advanced thermodynamic cycle in order to increase cooling power density. After preliminary test, like hydraulic and vacuum test, this prototype will be tested on a test station for adsorption cooling system, located in the laboratories of the C.N.R – I.T.A.E of Messina. Several kinds of test will be realized, changing the operating conditions and trying to optimize cooling power density. After, an estimate of energy consumption of the chiller will be carry out to evaluate a possible installation of a boat.

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## References

[1] R.E Critoph, Y. Zhong – *Review of trends in solid sorption refrigeration and heat pumping technology* – Proc. IMechE Part E.J Proc Mechanical Eng. 219 2005;

[2] R.Z. Wang, R.G. Oliveira – *Adsorption refrigeration: an efficient way to make good use of waste heat and solar energy* – Progr. Energy Combust. Sci. 32, 424-458;

[3] R. de Boer, S.F. Smeding – *Thermally operated air conditioning systems: development and test of a laboratory* – In: International Sorption Heat Pump Conference, September 23-26 Seoul, South Korea;

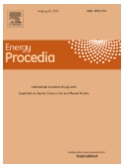
[4] S. Vasta, A. Freni, A. Sapienza, F. Costa, G. Restuccia – *Development and lab-test of a mobile adsorption air-conditioner* – International Journal of Refrigeration, Volume 35, Issue 03/05/2012, Pages 701-708 ;

[5] Yu.I. Aristov , A. Sapienza, D.S. Ovoshchnikov , A. Freni, G. Restuccia. – *Reallocation of adsorption and desorption times for optimization of cooling cycles* – International Journal of Refrigeration, Volume 35, Issue 03/05/2012 Pages 525-531;

[6] A. Sapienza, S. Santamaria, A. Frazzica, A. Freni – *Influence of the management strategy and operating conditions on the performance of an adsorption chiller* – Energy, Volume 36, Issue 09/09/2011, Pages 5532-5538;

[7] A. Freni, L. Bonaccorsi, L. Calabrese, A. Caprì, A. Frazzica, A. Sapienza – *SAPO-34 coated adsorbent heat exchanger for adsorption chillers* – Applied Thermal Engineering , Volume 85, 05/05/2015, Pages 1-7;

[8] Yu.I Aristov – *Challenging offers of material science for adsorption heat transformation: A review* – Applied Thermal Engineering, Volume 50, Issue 02/02/2013, Pages 1610-1618 ;




**Biography**

**Giuseppe Gullì** is a temporary research associate at the National Research Council at the Institute for Advanced Technologies for Energy (CNR-ITAE) in Messina. He received his master degree in Materials Engineering in 2013.